MAGNITUDE AND VARIATION IN THE CONTRIBUTION OF BANK EROSION TO THE SUSPENDED SEDIMENT LOAD OF THE RIVER SEVERN, UK

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ABSTRACT

The wide range of studies describing the role of bank erosion in fluvial sediment supply have mostly lumped amounts of bank erosion into coarse temporal units, such as years. This paper investigates sediment yields from individual bank erosion events within the upper River Severn, UK (basin area 380 km^2). Manual erosion pins and photo-electronic erosion pins were used to estimate bank erosion, and turbidity meters were used to determine suspended sediment transport. At the annual timescale, the silt-clay fraction of bank-derived sediment accounted for an equivalent of 17 per cent of the suspended load, increasing to an average of 38 per cent at the monthly timescale, and then to an average of 64 per cent at the event timescale. This research highlighted that for an upland catchment, bank erosion was an important supply of suspended sediment, and that for some flood events bank erosion can supply more sediment than is transported. © 1997 John Wiley & Sons, Ltd.

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KEY WORDS: bank erosion; bank sediment yield; suspended sediment load.

INTRODUCTION

Traditionally, reduced importance has been given to channel sources of sediment except during infrequent floods of high magnitude (Imeson *et al.,* 1984). However, bank erosion may contribute significant amounts of material to overall catchment sediment yields (Coldwell, 1957; Imeson and Jungerius; 1977; Grimshaw and Lewin, 1980; Trimble, 1993). The potential importance of bank erosion is illustrated by investigations of changing sediment yields downstream, where the increase in suspended sediment loads is attributed to bank inputs (Carson *et al.,* 1973; Church and Slaymaker, 1989). However, a large gap exists in understanding the relationship between bank erosion and suspended sediment dynamics, especially at the event timescale. Contributions of bank erosion and sediment characteristics are usually estimated over seasonal or annual timescales (Ashbridge, 1990, 1995), but not over individual flood events. Wide variations in figures on the importance of bank erosion contributions to suspended load also need reconciling. Estimates of the contribution of bank eroded material to river sediment systems vary from less than 5 per cent (Walling and Kane, 1984; Walling and Woodward, 1992) to over 80 per cent (Imeson, 1974; Imeson and Jungerius, 1977; Imeson *et al.,* 1984).

Controls affecting the contribution of banks have been investigated in detail and many studies have identified mechanisms and processes of erosion (Wolman, 1959; Hooke, 1979, 1980, 1986; Thorne, 1978, 1982, 1991; Lawler, 1984, 1987, 1993a). Controls act both spatially and temporally, the two most important being vegetation and bank soil properties. The relationship between bank erosion and vegetation is complex with many feedbacks and operates both temporally as vegetation varies throughout the year, and spatially as vegetation changes along the channel. Bank soil properties tend to be a spatial control on bank supply, but vary at a site during the passage of a flood.

Vegetation affects flow erosion, bank stability, bank accretion and bank stabilization. Flow erosion is affected by vegetation retarding the near-bank flow and damping turbulence which decreases entrainment by bursts and sweeps (Jackson, 1976; Leeder, 1983). This is complicated by vegetation bending when submerged

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(Kouwen and Li, 1979; Thorne, 1990). Vegetation reduces soil erodibility by resisting tension and increasing cohesion (Vidal, 1969; Kirkby and Morgan, 1980). Vegetated banks are better drained and drier, reducing the impact of moisture and loosening processes, which are a precursor to removal of material. Smith (1976) concluded that bank sediment with 16–18 per cent roots, with a 5 cm root mat, had 20 000 times more resistance to erosion compared with sediment without roots, while tensile strength of rooted samples can be ten times that of unrooted ones (Thorne, 1982). Waldron (1977) found that a mature stand of willows can provide 100 per cent more in shear strength than fallow land; however, dead vegetation can increase erosion of the bank. Relic roots and root holes provide preferential pathways for seepage that can lead to piping, usually followed by failure of overburdened banks (Imeson *et al.*, 1984). Feedback occurs when bank failure affects the vegetation, either by encouraging growth by providing fresh surfaces, or by discouraging growth by uprooting vegetation or burying it.

Soil properties and their interactions determine the magnitude of interparticle forces of cohesion that resist detachment and also influence the physical configuration of particles at the bank face (Grissinger, 1982). Properties affecting bank erodibility can be divided into primary soil properties, test conditions, composite soil properties and hydraulic properties (Grissinger 1982). Primary soil properties include mean particle size (Thorne, 1978), clay and organic matter content (Arulanandan *et al.*, 1973; Grissinger *et al.*, 1981; Thorne 1981), bulk density, and expressions related to exchangeable ionic strength (Grissinger, 1982). These vary spatially and govern interparticle surface attraction forces. Test conditions influence the rate of development of interparticle forces and include the temperature of the eroding water, antecedent moisture conditions, the rate of wetting, and pore water pressure (Arulanandran *et al.*, 1973; Grissinger *et al.*, 1981). All vary temporally with the flood hydrograph. Composite soil properties vary spatially and include Atterberg limits, penetration, dielectric dispersion (Arulanandan *et al.*, 1973; Thorne, 1981), permeability and volume characteristics (Grissinger, 1982). The most important hydraulic property is the fluid shear force, usually characterized by shear stress or tractive force, but lift forces and turbulence are also significantly related to bank erodibility.

Temperature can also affect bank contributions. The development of needle ice within the bank during winter periods reduces bank stability, increasing sediment supply (Lawler, 1986, 1993b). Long spells of dry weather loosen material which falls to the bed of the channel to await transport (Lawler, 1986). Intense periods of wetting and drying can also significantly weaken river banks (Twidale, 1964) and so aid erosion and sediment production.

The aim of this paper is to investigate the relationship between bank erosion and suspended sediment dynamics at the annual, monthly and event timescales. This is carried out by direct measurement of bank erosion and suspended sediment transport fluctuations at the event timescale.

STUDY CATCHMENT

This research is based on monitoring undertaken on the upper 35 km of the River Severn, UK (Figure 1). Monitoring sites were divided between the upper, experimental part of the catchment (8·7 km^2) and the River Severn immediately downstream as far as Caersws (catchment area 380 km^2). Within the experimental catchment, rock types are chiefly Ordovician and Silurian shales and mudstones with superficial deposits of stony boulder clay (M. D. Newson, 1976). Soils are typical of the upland UK, ranging from peat on the hilltops, podsols and gleys on valley slopes, with the occasional development of brown earths and peat bogs in valley bottoms (Rudeforth, 1970). The vegetation is predominantly plantation forest, of which 65·7 per cent is commercial forest (Sitka and Norway spruce) and 32·5 per cent is moorland and heathland (Kirby *et al.*, 1991). The climate is humid temperate, dominated by heavy, steady rainfalls caused by fronts and accentuated by orographic influences. Mean annual precipitation near the basin head is 2300 mm (A. J. Newson, 1976), but declines with altitude (Lawler, 1987). Downstream of the experimental catchment, the geology is mainly Silurian slaty mudstone and siltstone, on which fine loamy or silty soils develop. Monitoring sites are located on river alluvium with permeable silty soils overlying a gravelly subsoil (Bull, 1996). Vegetation is predominantly grass, used for grazing. The climate remains dominated by heavy, steady frontal rainfall.

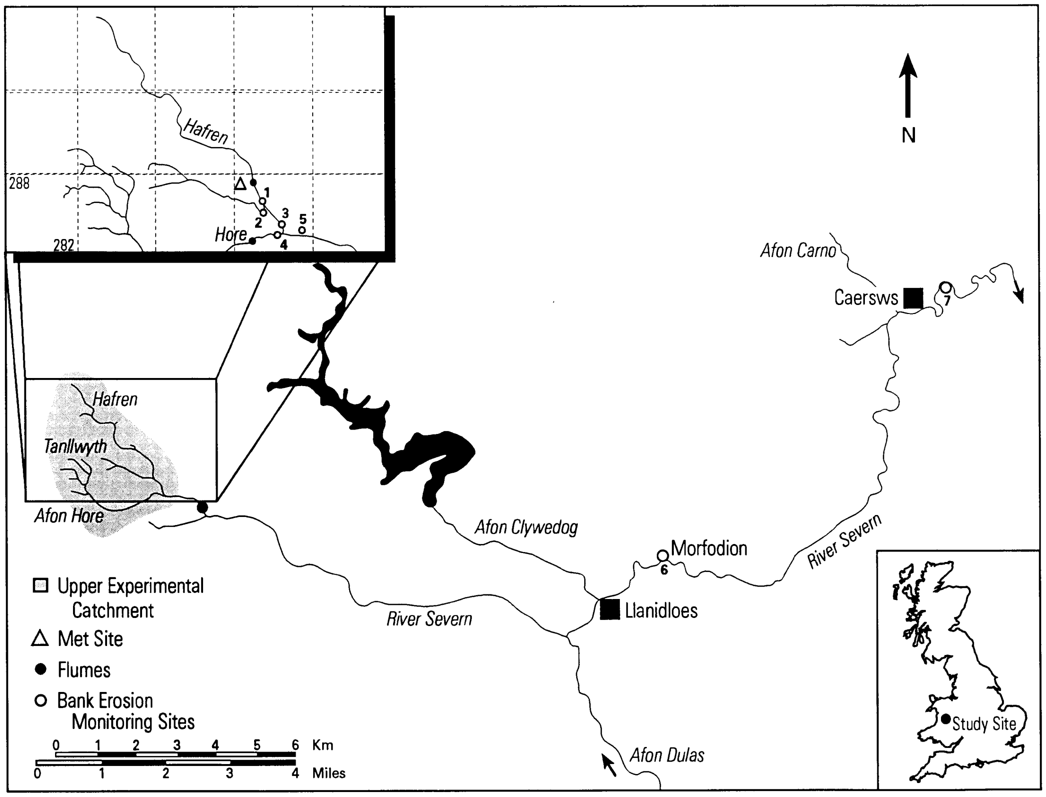

Figure 1. Study area

DATA COLLECTION

Seven sites representative of bank erosion rates and processes occurring in the upper Severn catchment were chosen for monitoring. Reconnaissance was carried out and evidence of possible erosional activity such as freshly exposed surfaces, limited vegetation growth, the presence of failed blocks, cracking, notches and overhangs was systematically recorded. Site selection was then based on the likelihood of erosion, the likely processes of bank erosion, existing instrumentation, site characteristics, previous research, limited artificial influences and accessibility.

At each site, dry bulk density was investigated using bulk density cans. Open-ended cans of known volume were driven into the bank face and then excavated so a plug of sediment was removed. Samples were brought back to the laboratory, removed from the cans, oven-dried for 24 hours and the sample weighed. The dry bulk density was then calculated by dividing the weight (kg) by the volume of the can (m^3). Bulk density samples were taken at five verticals along the bank face at one-third and two-thirds of the bank height. Measurements were made at the end of the monitoring period because of the disturbance caused to the bank and the likely effect on bank erosion rates and processes. For this paper an average dry bulk density is used for each site.

Particle size was determined at the same locations as dry bulk density by collecting bulk density samples. These were brought back to the laboratory, oven-dried for 24 hours and sieved. The weight of sediment for each size class was measured and percentages of the total sample calculated. An average was then calculated for each site which was used in the analysis. Averages were considered representative of all sites except site 7 where there was a marked difference in particle size between the upper and lower areas of the bank. However, an average was still used because the alternative was to carry out calculations for separate areas of the bank, which was more complicated and did not produce signficantly different results (Bull, 1996).

Bank erosion was monitored at all seven sites. Erosion rates were measured using a combination of manual and automated techniques so the complete bank zone was monitored. Erosion pins were arranged in grids of 18

Table I. Bank erosion rates and processes, and variables used in the calculations

Site	Rate of bank erosion ($cm\,a^{-1}$)	Bank erosion relative to channel width (%)	Bank erosion processes	Dry bulk density ($kg\,m^{-3}$)	Error in dry bulk density ($kg\,m^{-3}$)	Mean % silt and clay	Mean height (m)	Standard error in height (m)	Mean length (m)	Error in length (m)
1	1·29	0·323	Hydraulic action operating on 'prepared' banks	1092	0·7	29·0	0·80	0·07	10·00	0·02
2	4·88	0·976	Hydraulic action operating on 'prepared' banks, frost action	780	0·6	28·6	0·80	0·07	15·00	0·02
3	1·56	0·260	Hydraulic action operating on 'prepared' banks	1177	2·9	25·0	0·60	0·06	15·00	0·02
4	6·48	1·080	Hydraulic action operating on 'prepared' banks	1100	3·1	14·3	1·10	0·06	12·00	0·02
5	5·91	0·985	Hydraulic action operating on 'prepared' banks, piping	1177	2·9	25·0	1·20	0·06	15·00	0·02
6	22·47	1·170	Hydraulic action, undercutting, cantilever failure, frost action, desiccation, splash erosion, piping/sapping	1614	3·3	15·1	1·50	0·12	17·50	0·02
7	46·06	1·530	Hydraulic action, undercutting, cantilever failure, frost action, desiccation, splash erosion	1454	1·0	14·5	1·80	0·09	20·50	0·02

to 24 on the bank face at each site at 0·5 m intervals horizontally and at 0·3 m intervals vertically. Pins were constructed from 2 mm diameter silicone bronze welding rods with yellow heat-shrink ends to enable easy monitoring (Lawler, 1993a). Pin measurements were made on 41 occasions, at regular intervals and following major flood events. A recently developed automated erosion monitoring technique, the photo-electronic erosion pin (PEEP) system, was used to collect more precise data on the timing and magnitude of individual bank erosion events (Lawler, 1991). The PEEP system consists of photo-voltaic cells connected in series, which are housed in an acrylic tube. Following careful insertion into the bank face, subsequent bank retreat causes voltage output to rise. Changes in ambient light conditions are monitored by a reference cell. Both the cell series and reference cell are connected to a datalogger used to record data at 15 min intervals. PEEPs were located at sizes 2, 4, 6 and 7.

Suspended sediment transport was measured every 15 min using Partech IR40C turbidity sensors at sites 2, 4, 6 and 7. Turbidity meters have a low sensitivity to particles outside the silt-clay range (Gippel, 1989; Lawler, 1995), but for the purpose of calculating loads and understanding erosional processes a continuous record is preferable to discrete samples (Finlayson, 1985; Walling and Webb, 1981). Turbidity meters were calibrated using river sediment from fine deposits upstream of each site. Samples were oven-dried and sieved, and the sub-105 μm fraction used in dilution calibrations. This procedure resulted in calibration curves with R^2 values of 99 per cent, and mean standard errors of 3·94 $mg\,l^{-1}$. By using river sediment, inaccuracies arising from differences between the material used for calibration and the actual suspended sediment were limited, i.e. differences in colour, shape and particle size which affect turbidity (Gippel, 1989; Foster *et al.*, 1994). Sensor heads were located in the near-bank zone of the channel using metal booms, approximately 0·75 m from the bank toe. Single-point sampling of turbidity may raise questions of representativeness, but because straight sections of an upland channel were selected, strong mixing reduces these problems (Gippel, 1989).

Discharge data were obtained from fixed structures. For the upstream sites (2 and 4) discharge data were obtained from flumes maintained by the Institute of Hydrology (IH). For the lower sites (6 and 7) stage data were obtained from National Rivers Authority (NRA) gauging stations. The closest gauging stations to the monitoring sites were used, and no tributaries occurred between the gauging and monitoring sites. Stage data were in the form of charts, and were digitized, then converted to discharge using rating curves established by the NRA for the respective site.

CALCULATIONS

Calculations to complare bank sediment yield and suspended load were carried out for sites 2, 4, 6 and 7. The calculations are in units of weight only (kg); this differs from previous studies which have traditionally used

units of area and time as well as weight. However, using units of weight allows the total bank-derived sediment added in a reach to be directly compared with the amount of sediment transported through a particular reach, for specific time periods. The bank area producing the sediment varies from $8{\cdot}0\,m^2$ at site 1 to $36{\cdot}9\,m^2$ at site 7 (Table I), whilst catchment area varies from $3{\cdot}5\,km^2$ at site 1 to $380\,km^2$ at site 7. The areas used in the comparisons of sediment weight are therefore different, but are used in an attempt to understand the proportion of load accounted for by bank erosion. Units of time are considered by comparing inputs for individual floods, months and years.

Bank sediment yield was calculated using the following equation:

$$Q_{bs} = \bar{h} l \bar{r} \bar{b} \tag{1}$$

where Q_{bs} represents the bank sediment yield (in kg), $\bar{h}$ is the mean height of the bank face (in m), l is the length of the section (in m), $\bar{r}$ is the mean bank retreat (in m), and $\bar{b}$ is the mean dry bulk density of the section (in $kg\,m^{-3}$). Values of these variables are presented in Table I. This calculation was carried out for every pin and PEEP reading. Annual and monthly yields were calculated by summing the bank sediment yields that occurred in the relevant time periods. Errors associated with each estimate of bank sediment yield were calculated by combining the standard error in $\bar{h}$, $\bar{b}$ and $\bar{r}$, and the measurement error in $\bar{l}$.

Problems with this method of analysis include: mean values of bank height, retreat and bulk density are used; storage of sediment occurs within the channel; there are complications between the grain size of the bank face and the sediment transported in suspension and the representativeness of the monitoring sites. By using mean values in Equation 1 calculations of bank sediment yield were greatly simplified. Alternative methods would have involved dividing the bank face into a number of separate units, calculating yields for each unit, and then summing to calculate the sediment yield per event. This was attempted for a few measurements of bank retreat and compared to the method used here. However, the estimated bank sediment yield was similar, and well within the range of bank sediment yield calculated once errors had been taken into account (Bull, 1996).

Storage of sediment within the channel has many implications for the relationship between bank erosion supply and suspended sediment transport dynamics. Different processes are likely to lead to varying amounts of sediment moving into storage and this is complicated further by different bank erosion processes operating at different spatial scales. To include the effect of storage, nominal values of the amount of material moving into storage could be applied to each monitoring site. However, storage was not taken into consideration because firstly, accurate estimates of the amounts of sediment moving into storage cannot be made without detailed experimentation, and secondly, material is only likely to move into temporary storage until it is reworked by a later flood event. The sediment is likely to be transported at some point in time.

Differences in grain size also need to be taken into account when estimating the contribution of the banks to suspended sediment loads. It was assumed that only the silt and clay fraction of the bank-derived material would be transported as suspended sediment, although coarser fractions were also supplied by bank erosion. This assumption was supported by the analysis of suspended sediment samples taken during the study (Bull, 1996). The mean percentage of silt and clay was used to characterize each site.

Suspended sediment load was calculated for sites 2, 4, 6 and 7 from turbidity data. Suspended sediment concentrations were calculated by transforming the sensor output using the relevant calibration equation. Suspended sediment load transported during a single sediment transport event was then calculated using the following equation:

$$L_{ts} = \sum_{t_1}^{t_2} (Q_i C_i) \tag{2}$$

where L_{ts} represents the suspended sediment load (in $kg\,s^{-1}$), Q_i the discharge at time interval i (in $m^3\,s^{-1}$) and C_i the suspended sediment concentration (in $g\,l^{-1}$); t_1 and t_2 represent the time of the start and end of the flood, respectively. The suspended sediment load is therefore calculated for every transport event. A transport event is defined as the time period between the point at which suspended sediment concentration begins to increase, and the time when the concentration returns to this level. The start of the rise is usually distinct because of the flashy

nature of suspended sediment events. The return of suspended sediment concentration to the background level is more difficult to interpret during sequences of events. However, a transport event is deemed to have ended when the concentration begins to increase once more. During a single flood hydrograph there may be more than one sediment transport event. Most transport events lasted between one hour and one day. To calculate the monthly and annual suspended sediment loads, the loads transported for the floods occurring in the relevant time period are summed.

RESULTS

Bank erosion rates and processes

Processes of bank erosion are important in characterizing the supply of sediment to the channel at different sites. Small-scale subaerial activity produces individual particles which are easily transported, whilst large-scale mass failures dump large amounts of sediment into the channel producing a high initial sediment injection, then gradually release sediment during most floods. Processes of bank erosion were identified using a combination of methods including erosion pin results, PEEP time series records, photographic records, seasonality of retreat, coincidence with flood peaks, coincidence with extremes of temperature, and statistical analysis. Full details of the statistical analysis are presented in Bull (1996).

Table I presents the rates and processes of bank erosion for the study area. Each monitoring site had a unique pattern of bank erosion; however, there was evidence to support a 'bimodal' distribution of erosion, with most retreat occurring in winter, and a smaller peak of activity taking place in the summer. Processes of bank erosion varied between sites. Upstream sites were dominated by small-scale bank erosion, likely to be caused by hydraulic action attacking banks weakened by subaerial activity (Table I). Downstream sites had much larger rates of erosion, and processes were dominated by cantilever failure. Subaerial processes were superimposed on this. The number of bank erosion processes operating increased downstream, and large-scale failures were more frequent at downstream sites (Table I). Variability in bank erosion was evident at all sites, but was dominated by hysteresis between bank erosion and flood magnitude. As bank erosion rates and the occurrence of mass failures increase downstream, bank sediment supply increases.

Bank erosion rates measured during this study are similar to other studies on the Upper Severn. For example, Lawler and Leeks (1992) published data showing single bank erosion events varying from 0·5 to 0·8 m on the Afon Tanllwyth. Thorne and Tovey (1981) recorded bank erosion rates of 0·28 m a^{-1} for cohesive material at Morfodion, but demonstrated that overall rates were greater because of cantilever failure. Thorne and Lewin (1979) published average erosion rates of 0·5 m a^{-1} at Caersws, but erosion varied between 0·35 and 0·6 m a^{-1}.

Contributions of bank erosion to the fluvial system

Table II shows that the total load added to the channel from bank erosion generally increased downstream. A similar trend was observed when the proportion of sediment less than 63 μm was considered. This was expected because both the rate of bank erosion and the bank height increased downstream.

Figure 2 shows monthly bank sediment yield for each monitoring site. At sites 1, 2 and 3 inputs of sediment from bank erosion are clustered in the winter months, with only a few months with significant inputs of sediment during the summer. At sites 4 and 5 monthly bank sediment yield tends to increase, and inputs become much more variable. Inputs occurred mostly during the winter, but also during the summer of the first year of study. At the two downstream sites (6 and 7) monthly bank sediment yield continues to increase. Many more months experience inputs of sediment from bank erosion than at the upstream sites. At site 6, June 1994 and January 1995 experience large inputs of bank sediment, which account for approximately 40 per cent of the bank sediment yield over the whole study period. At site 7 very large inputs of sediment occur in January 1994 and January 1995. These again account for most of the bank-derived inputs occurring throughout the study (approximately 70 per cent). Thus a few events may supply most of the bank-derived sediment to the system.

Figure 3 shows bank sediment yields calculated for every retreat recorded by the PEEPs. At site 2, bank erosion occurs throughout the year. There are 15 bank sediment additions, which on average supplied

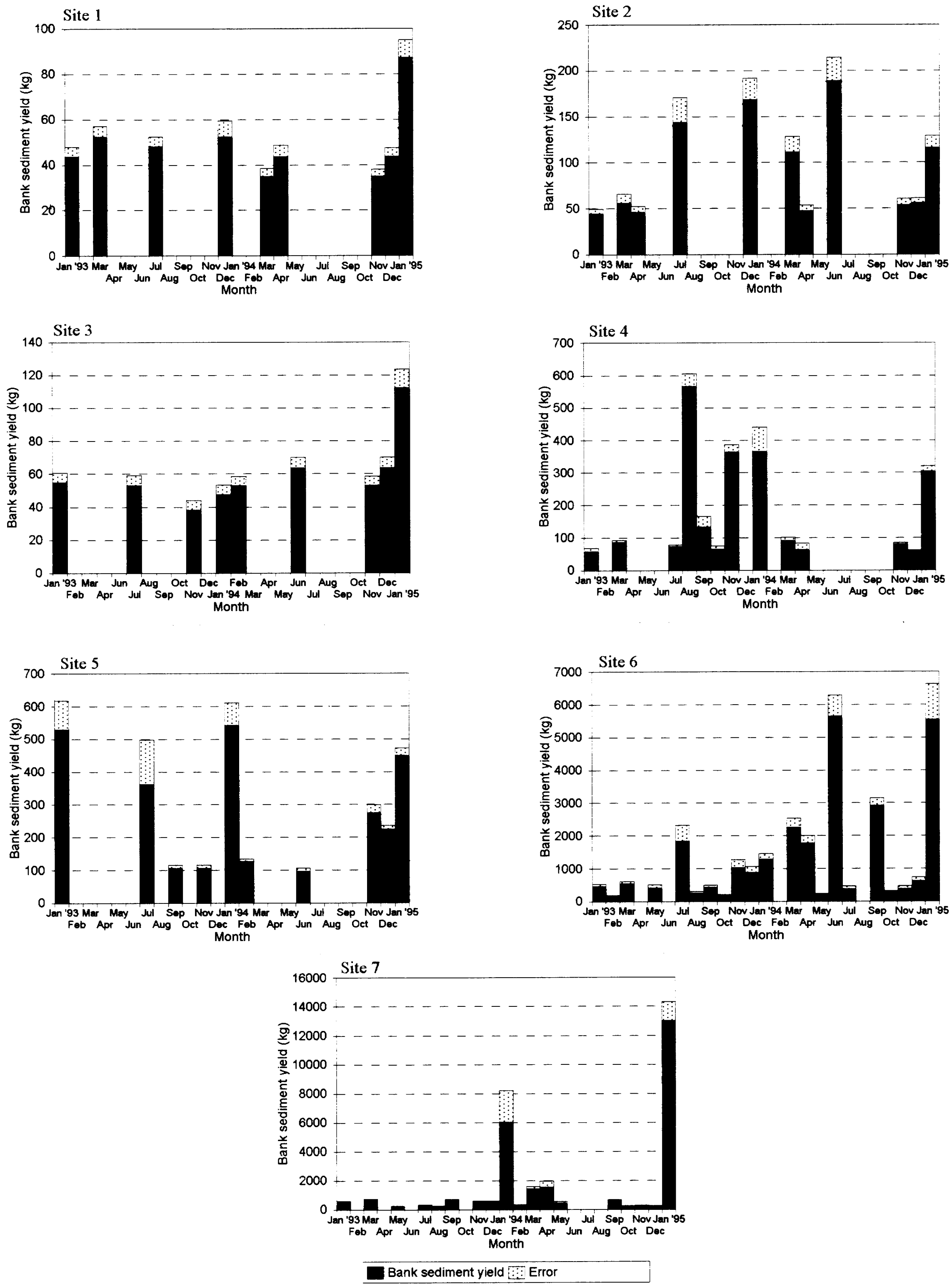

Figure 2. Monthly bank sediment yields at sites 1 to 7. DBA: site 2, 4 km^2; site 4, 4 km^2; site 6, 170 km^2; site 7, 380 km^2

Table II. Estimates of the average annual bank sediment yield (Q_{tb}), the silt-clay fraction of the annual bank sediment yield (Q_{tsc}), the annual load (Q_{ts}), the proportion of the total load accounted for by the bank sediment yield (%*BE*) and the silt-clay fraction of the bank sediment (%BE_{sc}) for each site

Site	Q_{tb} (t)	Q_{tsc} (t)	Q_{ts} (t)	Annual load ($t\,km^{-2}\,a^{-1}$)	%*BE*	%BE_{sc}
2	0·443–0·588	0·127–0·168	1·41–1·67	0·705–0·835	31–35	9–10
4	1·030–1·280	0·147–0·183	0·78–1·02	0·446–0·583	132–125	18–18
6	11·666–15·931	1·762–2·406	8·27–8·38	0·048–0·049	141–190	21–29
7	11·372–16·247	1·649–2·356	90·20–93·12	0·237–0·245	13–17	2–3

approximately 60 kg of sediment per event (except when no bank erosion occurs). The maximum addition of sediment greatly exceeds this (700 kg on 26 May 1994). At site 4 there were less sediment input events (7), and additions of sediment at this site show a clear distinction between the two years of monitoring. For the first year, sediment inputs from bank erosion are about 200 kg, but for the second year of study there is a drop to around 50 kg per event. This is likely to be related to the bank erosion processes occurring.

The downstream sites (6 and 7) experience more additions of bank-derived sediment (49 and 40 times, respectively) and inputs of sediment increase compared to upstream sites. At site 6 there was a large event on 29 May 1994 which supplied almost 18 per cent of the total suspended sediment load at this site. At site 7 similar events occurred on 21 December 1993 and on 28 December 1994 which supplied 67 per cent of the total estimated bank-derived sediment at this site. These large events were produced by undercutting and subsequent failure of the cantilever overhangs, and supplied most of the sediment to the system.

Estimates of suspended sediment load

Estimates of annual suspended load are presented in Table II. These appear low in national and international terms, and are an order of magnitude less than previously presented research (e.g. Leeks and Newson, 1989; Kirby *et al.*, 1991). This is likely to be related to the method of calculation, and the dominant weather conditions during the study. Suspended sediment loads were calculated by integrating the suspended sediment concentration during individual flood events. Thus any sediment transported between flood events is not included in estimates of total load. However, suspended sediment transport between flood events is negligible for the River Severn, with concentrations usually less than 5 $mg\,l^{-1}$ (Leeks, personal communication), and if suspended sediment transport is calculated at this level for the rest of the year, estimates of annual suspended sediment load remain low. The study also took place during a relatively dry period, so the frequency of suspended sediment transport events was below average.

Figure 4 shows monthly variations in suspended sediment load transported at the monitoring sites. For the two upstream sites the data began in June 1994 and at site 6 the turbidity sensor located was not working for the final two months of the study. At site 2 there does not appear to be a general pattern, and the load is highly variable. At site 4 the monthly suspended sediment loads are still variable, but tend to be lower than at site 2. The load transported increases at site 6 and at site 7. Load is highly variable at both of these sites and may be related to the variability of inputs from bank erosion, but is also likely to be influenced by in-channel stores of sediment and their dynamics. At site 6, August 1994 accounts for about 50 per cent of the total load. At site 7 there is a similar occurrence in September 1994 which accounts for 50 per cent of the total load.

Figure 5 shows suspended loads transported during individual events. At site 2 there is a large number of transport events (27 transport events in six months) with relatively low suspended sediment loads. These are concentrated in September and December. Suspended loads are relatively constant compared with the other sites. At site 4 there are fewer suspended sediment transport events (18 in six months), and these are again variable. Loads are slightly lower than at site 2, and transport is centred on September and October. Further downstream at site 6, suspended sediment transport is distributed more evenly throughout the year. There is a total of 29 transport events. Suspended sediment loads are greater than at the upstream sites, and loads are highly variable. At site 7, suspended sediment transport occurs throughout the year with 62 transport events recorded. Transport occurs during most months, but the largest amounts of sediment are transported during September, October and December, especially during the second year of study. Loads are much greater than at the other monitoring sites, and the variability remains high.

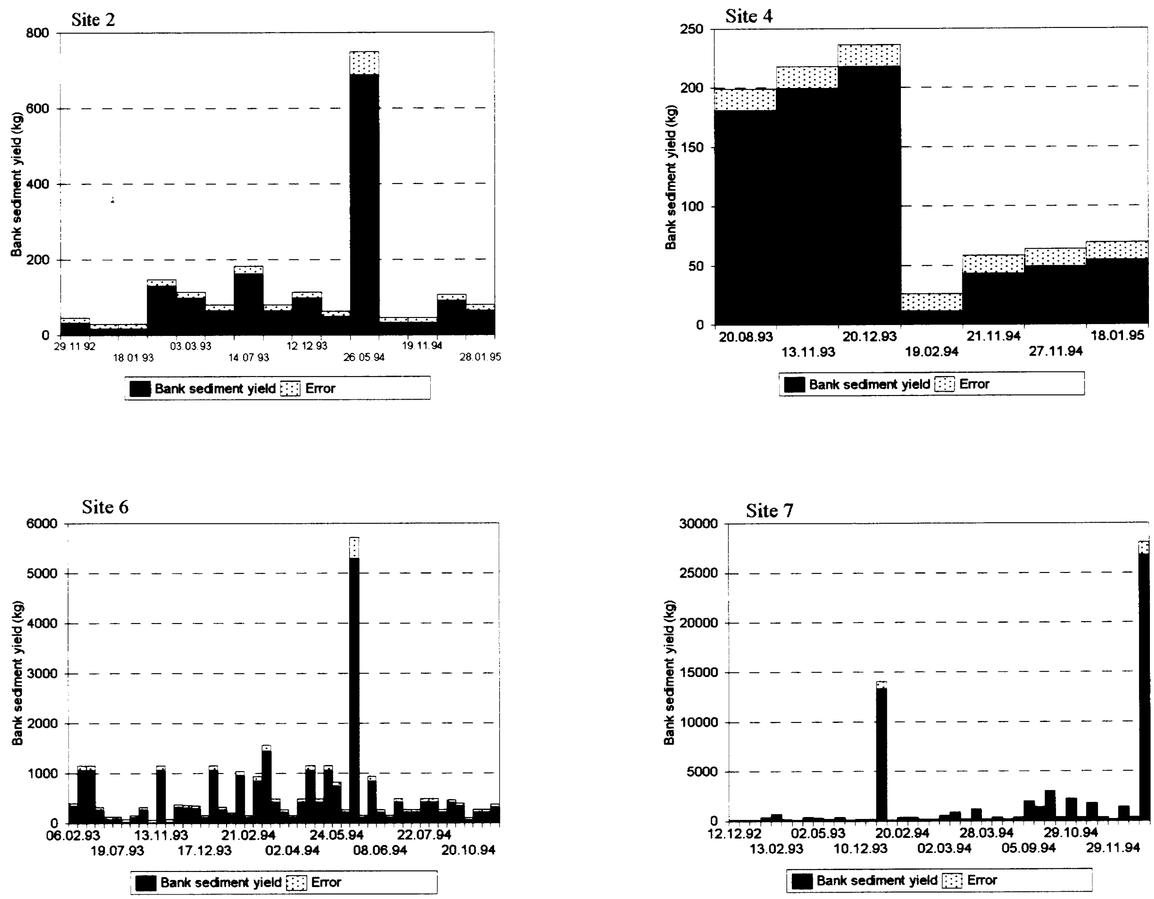

Figure 3. Event bank sediment yields at sites 2, 4, 6 and 7

The comparison of bank sediment yield and suspended sediment load

Table II shows the difference between the annual bank sediment yield and the annual suspended sediment load at sites 2, 4, 6 and 7. Bank erosion supply includes the full range of sediment sizes that occur in the bank (from clay to gravel), but the analysis presented here concentrates on the silt and clay fraction of bank-derived sediment because this is the size range likely to be transported in suspension. Where values of the percentage of sediment accounted for by bank erosion are greater than 100 per cent, annual bank erosion supply exceeds the annual suspended load. The excess sediment moves into storage. Storage of sediment was evident during site visits as fine wash deposits at the bank toe and on bar tops, and also as failed blocks which had come to rest within the bank toe zone. Storage occurs at sites 4 and 6 when the total bank-derived sediment is considered; however, when the silt and clay fraction is investigated, the proportion of load accounted for bank-supplied material falls to 18 per cent at site 4, and between 21 and 29 per cent at site 6. Thus, the silt and clay fraction of bank-supplied material provides a maximum amount of sediment at site 6 (29 per cent) and a minimum at site 7 (2 per cent).

At monthly timescale, bank erosion inputs at site 2 account for between 4 and 102 per cent of the suspended sediment load. However, if the bank inputs in June are compared to the suspended sediment transported during the following month, bank-derived sediment may exceed the load transported (Figures 2 and 4). This highlights differences between the supply and transport of sediment. It is unlikely that there is a direct relationship between bank erosion supply and transport of the sediment (Ashbridge, 1990, 1995). Thus sediment may be supplied, move into temporary storage, and be transported during a later flood.

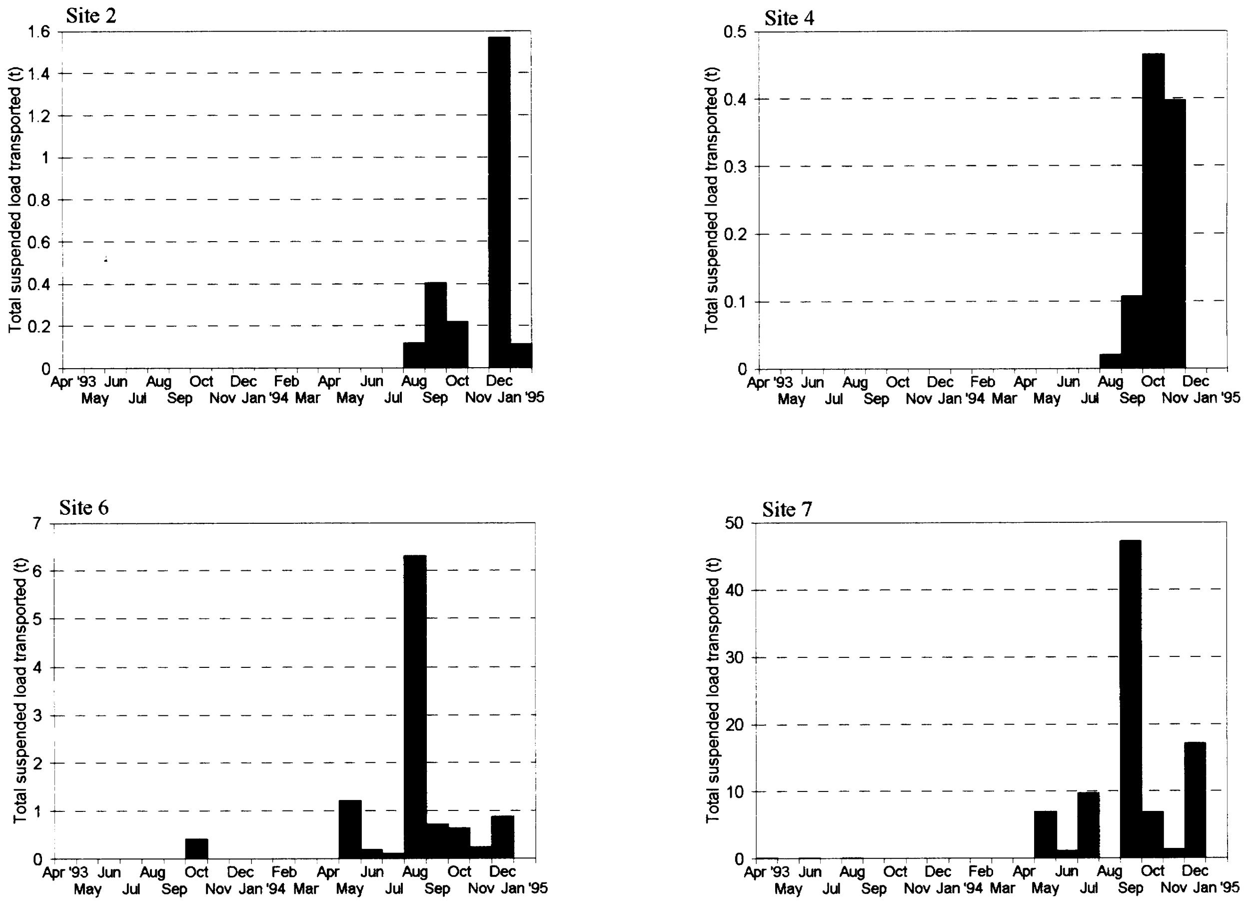

Figure 4. Monthly suspended sediment loads at sites 2, 4, 6 and 7.
Note that no data exists before August 1994 for sites 1 and 2

At site 4, the dominant period of suspended sediment transport is from August 1994 to November 1994 (Figure 4). Bank erosion occurred during November, accounting for approximately 25 per cent of the load. Bank sediment inputs to the channel occur during March 1994 and April 1994, before most suspended sediment is transported. Thus sediment is again likely to move into storage until sediment is transported by events later in the year.

At site 6, the major period of suspended sediment transport was from May 1994 to November 1994 (Figure 4). All these months experienced additions of bank-derived sediment except August 1994. The larger amounts of bank retreat occurred during June 1994 and September 1994. These are not the months when most sediment is transported, but major bank additions precede the months when most sediment is transported (August 1994 and October 1994). Bank erosion accounts for a maximum of 55 per cent of the monthly suspended sediment transport.

At site 7, the main period of suspended sediment transport is from September 1994 to December 1994. Additions of bank sediment also occur at this time, but are much lower than for the same period the previous year. The period September 1994 to December 1994 was when one of the breaks in the turbidity record occurred, so additions of sediment and the load transported cannot be compared. However, for this second winter, bank-derived sediment accounts for less than 20 per cent of the suspended sediment load.

At the event timescale many estimates of total bank sediment supply exceed the suspended sediment transported, especially at sites 6 and 7 (i.e. values > 100 per cent in Table III). This is likely to be caused by cantilevers adding blocks of sediment to the channel. When the silt and clay fraction is considered, only one

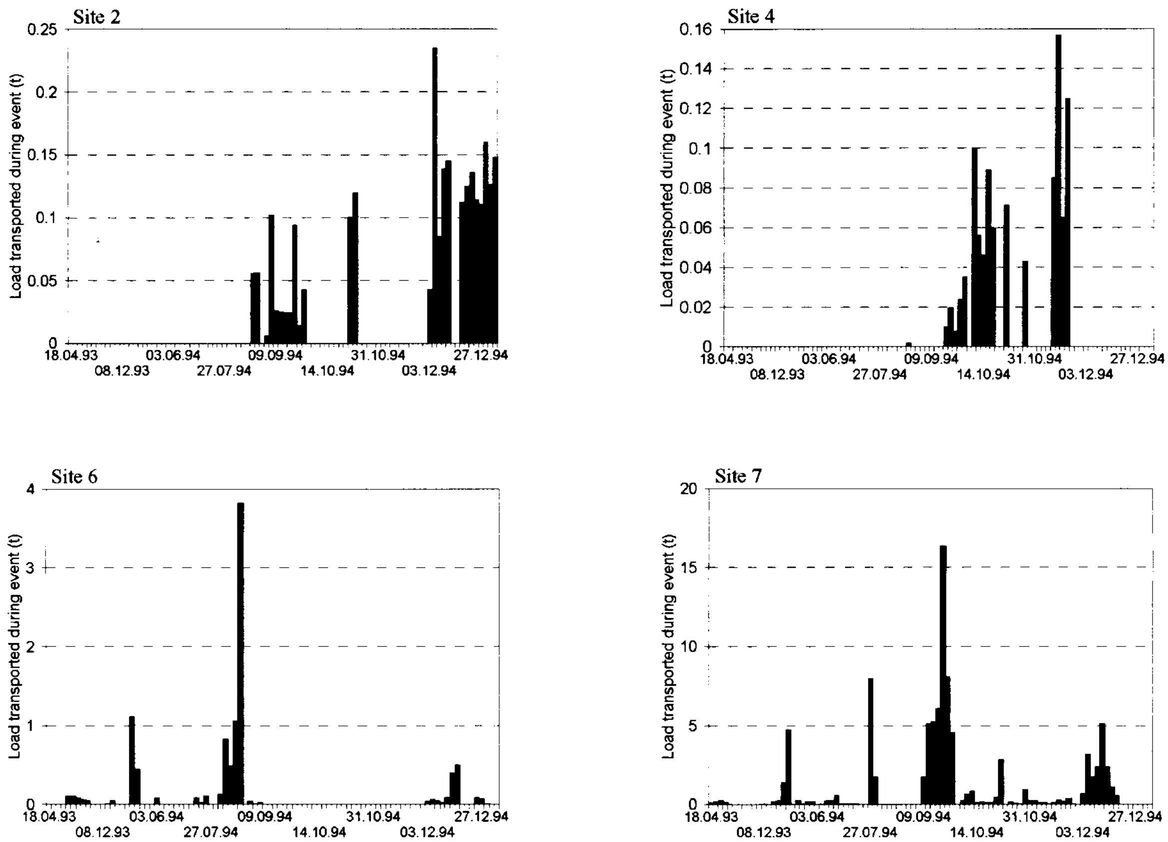

Figure 5. Event suspended sediment loads at sites 2, 4, 6 and 7.
Note that no data exist before August 1994 for sites 2 and 4

Table III. Analysis of coincidental bank sediment inputs and transport events. Q_b represents the event bank sediment yield, Q_{sc} the silt-clay fraction of the event bank sediment yield, and Q_s the event suspended sediment yield

Date	Site	Q_b (t)	Q_{sc} (t)	Q_s (t)	%*BE*	%BE_{sc}
15.10.93	6	0·174–0·206	0·026–0·032	0·085	205–242	30–38
08.12.93	7	0·437–0·563	0·061–0·079	0·036	1213–1561	169–219
09.05.94	7	0·294–0·546	0·041–0·075	0·174	169–313	23–43
15.05.94	6	0·181–0·239	0·028–0·036	1·108	16–22	2–3
23.06.94	6	3·542–4·178	0·534–0·630	0·240	1476–1741	223–263
01.09.94	6	2·686–3·154	0·406–0·476	0·038	7068–8300	1068–1253
09.09.94	7	0·310–0·490	0·043–0·067	0·714	18–29	3–4
19.09.94	7	0·226–0·294	0·031–0·039	4·570	5–6	1–1
25.10.94	7	0·162–0·258	0·029–0·035	0·136	119–189	21–26
15.11.94	7	0·124–0·296	0·023–0·037	0·040	310–740	58–93
08.12.94	2	0·055–0·064	0·013–0·017	0·146	38–44	9–12
09.12.94	7	0·133–0·247	0·019–0·034	2·371	6–11	1–2
04.01.95	2	0·108–0·132	0·029–0·037	0·112	96–117	26–33

event occurs when bank erosion supply exceeds the load transported (Table III). Thus, at the event time-scale the silt and clay fraction of bank-supplied sediment accounts for a minimum of 1 per cent of suspended sediment load transported, and a maximum of 1253 per cent of suspended load. At site 2 bank-derived sediment tends to account for between 9 and 33 per cent of the suspended load transported. No bank sediment yield and suspended sediment transport events coincided at site 4. At site 6 the importance of bank sediment varies from 2 to 263 per cent. At site 7 the amount of load potentially supplied by bank erosion is again variable. On one occasion, bank-

derived sediment exceeds the load transported, and during another event the supplied sediment approaches 100 per cent of the load transported. For the remaining events, bank sediment potentially supplies between 1 and 43 per cent of the load transported.

By closer scrutiny, events were identified where bank erosion preceded transport without the occurrence of a flood in between. Relationships between bank erosion and suspended sediment transport were also investigated for these events. For this to be valid it must be assumed that the sediment supplied is freely available for transport and is subject to only minor disturbance during the intervening time period. When bank inputs precede suspended sediment transport, the potential for bank erosion to supply material is greater than when events coincide, although the frequency with which supply exceeds transport is less. Bank erosion additions of sediment at upstream sites become more important than when bank erosion supply precedes transport. When the silt and clay fraction is considered at site 2, bank inputs account for between 10 and 102 per cent of the load. At site 4, sediment supplied by bank erosion accounts for 8 to 29 per cent of the load. At site 6, one event contributes more material than is transported, and the other between 75 and 87 per cent. At site 7, material supplied preceding suspended sediment transport accounts for similar proportions as supplied when events are coincident.

DISCUSSION

The spatial and temporal variation in the amount of sediment derived from bank erosion processes operating at each site. The variability in inputs of bank-derived sediment is likely to relate to the number of different processes operating. Inputs are more variable at downstream sites, where a greater number of bank erosion processes operate. The variability increases dramatically when mass failures begin to operate (at site 6), because large-magnitude erosion events produce large inputs of bank-derived sediment to the channel, although small erosion events produced by hydraulic action continue to occur.

The variability in the proportion of suspended load potentially accounted for by bank erosion is likely to be related to the natural variability inherent in bank erosion rates and processes, as well as the complex relationship between runoff and sediment stores. This is complicated further by the nature of different flood events. During some floods, bank erosion does not occur, so sediment must be derived from catchment sources of sediment and/or sediment stores within the channel. However, at other times large-scale failure of the banks may occur during a flood, and much of this sediment may move directly into transport, supplying all the sediment transported. Table III highlights the potential importance of bank erosion inputs to the channel and the great variability.

At site 6, when annual relationships were investigated, bank-derived sediment appeared to have most importance in supplying sediment compared with the other sites. As the timescale was decreased it became apparent that the silt-clay fraction of bank-derived sediment could potentially supply all the suspended sediment transported on a monthly and an event basis. The rate of bank erosion at site 6 was $0{\cdot}234\,\mathrm{m\,a^{-1}}$ (Table I) and bank erosion occurred throughout the year. Bank erosion processes were dominated by cantilever failure, and there was a well-developed bank toe zone. Many blocks were deposited in the channel and these may account for most of the suspended sediment transported. These blocks form an ongoing supply of sediment to the channel. Thus, sources of bank-derived sediment are readily available throughout the year, whether or not bank erosion occurs coincident with transport events. Bank preparation processes also occurred at this site. These act to weaken the bank face, but also affect deposited blocks of sediment. This is likely to aid particle entrainment and increase the importance of bank sediment with respect to the suspended sediment load.

Site 7 had the greatest rate of bank retreat, but this did not account for a large amount of suspended sediment load transported. The importance of bank supply increased as finer timescales were investigated. On one occasion the silt-clay fraction of bank-derived sediment exceeded the suspended load transported. On another event, bank supply accounted for 93 per cent of the load. However, usually bank supply accounted for between 1 and 43 per cent of the load. The pattern of bank supply is likely to be related to the nature of cantilever failure at this site. Cantilever failure was the dominant process of bank erosion, but only one cycle of undercutting and subsequent collapse occurred each year. Some of these blocks were also deposited on the floodplain during overbank flow. These results were not directly included in the analysis, but it means that the blocks do not

always provide a sediment source within the channel. If blocks had been deposited in the channel, sediment would continue to be available for transport, and this may have increased the importance of bank sediment sources.

Results suggest that there may be two conceptual models of bank erosion supply to the channel. The first model applies when bank erosion and an increase in suspended sediment load occur during the same flood event. Bank erosion may be caused by the rise in stage combined with preparation processes such as frost action or increased bank moisture content. The bank-derived sediment is added to the flow as individual particles, which are easily transported, and moved out of the reach. Bank erosion produced by mass failure may also add sediment to the channel during the same flood that transports material. However, material is supplied in blocks. Most of this sediment is likely to move into temporary storage, and only some will be transported directly. The proportion transported directly is likely to depend on the size of the block, the particle size of the material, the presence of vegetation and the magnitude of the flow. Not all the sediment supplied by bank erosion is transported from the reach.

The alternative model applies when material is supplied to the channel between floods, or during a flood where limited suspended sediment transport occurs, and bank-derived sediment is moved into temporary storage. Thus bank-derived material is available for transport during the following flood, even though active bank erosion may not occur. This is especially likely to occur where mass failures are active. Thus blocks deposited in the channel are gradually eroded over a series of floods, continuing to supply bank-derived sediment to the channel long after failure has occurred.

CONCLUSION

Results have shown that, throughout an upstream channel network, bank erosion has the potential to supply most of the sediment transported for some flood events. The importance of bank erosion in supplying sediment for transport varies between sites and becomes more important at the event timescale. The variability in the importance of bank supply increases downstream and at finer timescales. This is likely to reflect changing bank erosion processes downstream. However, patterns of sediment delivery and transport are complicated by sediment moving into storage. These stores of material are accessed at different times on individual flood events, and by floods of different magnitudes. This results in complex patterns of sediment supply from the channel margins. This may have implications for suspended sediment transport models, which should include bank erosion as an important but highly variable sediment supply during individual events.

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